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The effect of particle size distribution of tailings on rheological characterization of paste

Introduction

Mine tailings are by-products resulting from physical or physicochemical processes in mineral beneficiation plants. Various challenges arise when disposing of these high-water-content tailings in dams using conventional methods, which also require large land areas with suitable topography. The main risk associated with tailings dams, the most common storage method worldwide, is dam failure due to uncontrolled deposition, leading to the release of pollutants and severe environmental disasters (Giustozzi et al. 2018; Owen et al. 2020). To address these problems, disposal methods that better account for environmental risks have been increasingly explored (Bascetin et al. 2018; Tuylu et al. 2019; Chen et al. 2022; Tuylu 2022a).

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Among these, paste technology has emerged as a more environmentally friendly storage and disposal approach. This method minimizes the risks associated with traditional slurry disposal and has gained increasing importance in recent years. Paste technology is defined as a fine-grained, pumpable material obtained by dewatering tailings and mixing them with a controlled amount of water and, when necessary, binder or additive materials. It can be applied both underground (cemented) and on the surface (cemented or uncemented) and offers major advantages such as reducing water consumption and minimizing the release of contaminated process water (Henriquez and Simms 2009; Deschamps et al. 2011; Liu et al. 2016; Bascetin et al. 2021, 2022; Tuylu 2022b; Bascetin et al. 2023).

In both underground and surface applications of paste technology, the flow behavior of the material is critical since the paste is pumped to the final deposition area. The applicability of the method therefore, depends on the paste being sufficiently fluid and pumpable (Verkerk and Marcus, 1988; Jiang and Fall 2017; Adiguzel and Bascetin 2019). From a rheological perspective, paste materials exhibit non-Newtonian flow behavior that cannot be described by a single parameter. Kinetic energy losses occur during flow due to multiple factors, and there is no fixed ratio between shear stress and shear rate; viscosity varies with both. For these reasons, the flow behavior of paste materials remains a topic of ongoing research (Ouattara et al. 2017; Adiguzel and Bascetin 2019; Sanchez-Peralta et al. 2020).

Previous studies have identified several parameters influencing paste rheology:

- solid content,
- binder ratio,
- mineral or chemical additives,
- curing conditions,
- the physical, chemical, and mineralogical properties of the tailings.

Among these, an increase in solid content generally decreases fluidity, leading to higher viscosity and yield stress (Chen et al. 2016). Cement is the most common binder, and its ratio is adjusted according to the desired strength. Its effect on rheology, however, varies with the type of tailings: studies on silica and iron tailings found no significant influence (Lang et al. 2015; Qiu et al. 2020), whereas research on gold and coal tailings reported clear effects (Yue et al. 2016; Cao et al. 2021).

Environmental conditions, particularly temperature, also play a major role. While higher temperatures can increase fluidity by reducing viscosity, in cemented pastes, they may accelerate cement hydration (C–S–H formation), increasing yield stress (Yang et al. 2022). Additionally, the colloidal properties of the mixture, influenced by both tailings size and mineralogy, strongly affect flow behavior (Landriault 2001; Adiguzel and Bascetin 2019). Zeta potential measurements are commonly used to characterize these effects: higher zeta potential values increase particle repulsion and stability, whereas lower values promote aggregation (Reyes et al. 2019; Robles et al. 2019; Zhang et al. 2020).

Regarding physical characteristics, the particle size distribution (PSD) of tailings is one of the most influential parameters governing paste rheology (Kwak et al. 2005; Yue et al. 2016; Cheng et al. 2020; Yang et al. 2021). Macroscopic rheological behavior is determined by the impact of microscopic particle interactions, friction, and packing, which are more pronounced at small particle sizes and high solid contents (Brito et al. 2021). Because mine tailings are inherently heterogeneous, the properties of paste mixtures can vary substantially with PSD. Studies have reported exponential relationships between slump height and yield stress (Zhou et al. 2022) and strong correlations between slurry concentration and yield stress (Zhang et al. 2018). In unclassified tailings, yield stress tends to increase with shear rate and decrease with shear time (Li et al. 2020).

For mining operations adopting paste technology, understanding how PSD affects pumpability is crucial for designing tailings-specific mixtures. Since particle size influences the pore structure and thus yield stress, smaller particles generally increase yield stress (Deng et al. 2018; Brito et al. 2021). However, this relationship has not been systematically demonstrated for different tailings types (Adiguzel and Bascetin 2019; Cheng et al. 2020). Moreover, existing research has focused mainly on the fine fraction (<20 μm), and the broader PSD influence remains underexplored.

In recent years, growing attention has been given to the rheological and mechanical behavior of cemented tailings backfill systems in the context of sustainable tailings management. Recent studies have demonstrated that the rheological performance of paste mixtures is closely related not only to particle size distribution (PSD) and curvature coefficient (Cc), but also to the mineralogical and chemical composition of the tailings and binders. Tuylu (2022b) reported that the incorporation of zeolite into cemented paste backfill improved cohesion and reduced bleeding at similar solid fractions, whereas Wang et al. (2025) and Chen et al. (2022) highlighted the influence of curing stress on the mechanical characteristics and damage constitutive behavior of CPB. Advanced modeling approaches proposed by Zhang et al. (2023) and sustainability-oriented reviews by Wu et al. (2024) further emphasized the importance of rheological control in achieving stable and pumpable backfill systems. Moreover, recent investigations have underlined the critical role of binder and clay composition in governing flowability and strength. For instance, Menasria et al. (2025) demonstrated that the free muscovite content in tailings significantly affects the consistency, yield stress, and viscosity of CPB; similarly, Koltsakidis et al. (2023) showed that increasing bentonite binder concentration (40–60 wt.%) in zeolitic pastes enhances cohesion, yield stress, and compressive strength while maintaining shear-thinning behavior. Complementary to these, Girskas et al. (2023) observed that SO_3 and clay content in zeolite-based composites substantially alter viscosity and structural stability, confirming the strong link between chemical composition and rheological response. Additionally, Sharma and Goel (2022) reviewed the fundamental rheological behavior of tailings materials, while Nazar et al. (2023) and Amangeldi et al. (2021) introduced machine learning and iterative modeling approaches for predicting yield stress and viscosity in non-Newtonian materials. Most recently, Deng et al. (2025) proposed a piecewise rheological model for metal tailing slurries that integrates particle concentration and shear rate effects into a unified predictive framework. Collectively, these studies provide a solid theoretical and experimental foundation for interpreting how curvature coefficient (Cc), particle size distribution, and compositional variability jointly govern the rheological and mechanical performance of tailings-based pastes, thus strengthening the motivation and novelty of the present work.

The main objective of this study is to investigate how tailings size distribution, homogeneity, and fine material content influence paste rheology. The effects of clay content are also assessed. While previous works have largely focused on the influence of binders or additives, the present study examines the intrinsic effect of PSD by comparing tailings from six different mines (iron, boron, silica, gold, marble, and copper) and analyzing their relationship with the curvature coefficient (Cc) and uniformity coefficient (Cu), two key indicators of grain size distribution. The study aims to determine the mixtures that achieve the desired pumpability based on tailings PSD characteristics and to enable early identification of pumpability issues arising from PSD variations in paste disposal operations.

1. Materials

Process tailings from iron, boron, silica, gold, marble, and copper mines located in different regions of Türkiye were used in this study. Some of their physical and chemical properties, along with the sample codes used, are listed in Table 1, and the corresponding particle size distribution (PSD) curves are presented in Figure 1.

As seen in Table 1, the mine tailings exhibit complex and highly variable chemical compositions. The oxides (SiO_2, SO_3, Fe_2O_3, Al_2O_3, etc.) differ significantly among tailings,

Table 1. Physical and chemical properties of tailings

Tabela 1. Właściwości fizyczne i chemiczne odpadów przeróbczych

	Iron mine tailings	Boron mine tailings	Silica mine tailings	Gold mine tailings	Marble mine tailings	Copper mine tailings
Code	FeT	BT	SiT	AuT	MT	CuT
Density (g/cm^3)	2.93	2.65	2.77	2.74	2.75	3.38
Specific surface area (m^2/g)	21.72	6.70	20.63	11.59	6.33	11.46
SiO_2 (%)	49.60	17.20	83.90	42.30	1.00	26.50
SO_3 (%)	0.14	0.69	0.10	19.50	–	25.10
Fe_2O_3 (%)	30.00	0.37	0.74	7.41	0.10	30.60
Al_2O_3 (%)	10.80	1.03	9.03	11.20	0.10	7.76
MgO (%)	1.01	9.32	0.17	1.69	1.00	3.34
Na_2O (%)	1.86	0.23	0.19	0.70	0.10	–
CaO (%)	1.17	68.20	0.10	11.20	55.00	4.87
K_2O (%)	4.24	0.23	2.22	2.76	–	0.38
SrO (%)	–	2.51	–	–	–	–

reflecting the mineralogical diversity of their source deposits. The particle size distribution curves shown in Figure 1 also vary notably across the six tailing types. The characteristic diameters (d_{10}, d_{30}, d_{50}, d_{60}, d_{90}) and the calculated uniformity coefficient (Cu) and curvature coefficient (Cc) values are given in Table 2.

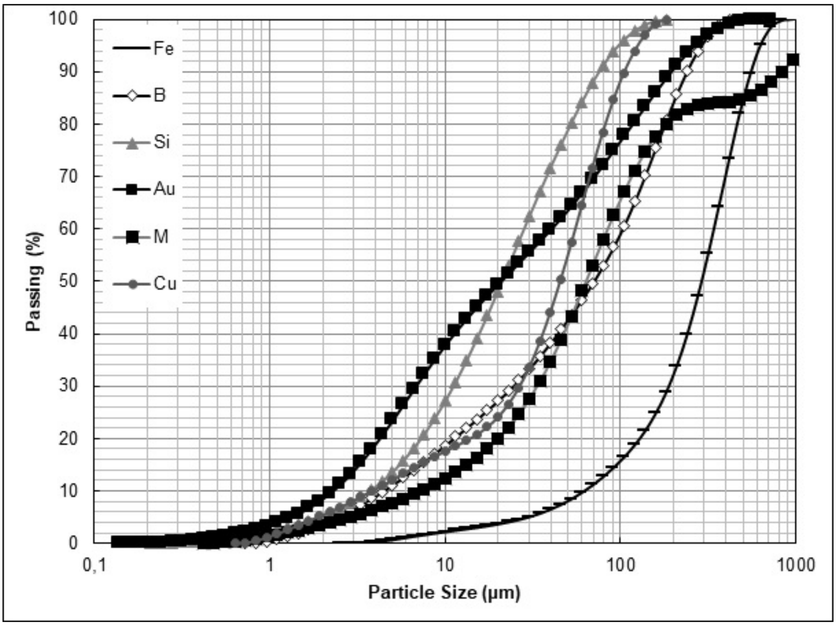

Fig. 1. Particle size distribution curve of tailings

Rys. 1. Krzywa rozkładu wielkości cząstek odpadów

Table 2. Particle size of tailings

Tabela 2. Wielkość cząstek w odpadach po przeróbce

Tailings	FeT	BT	SiT	AuT	MT	CuT
d_{10} (μm)	62	5	4	2	7	4
d_{30} (μm)	201	23	12	7	35	26
d_{50} (μm)	289	70	21	21	64	45
d_{60} (μm)	340	105	28	40	89	59
d_{90} (μm)	554	238	76	194	833	105
–20 μm (%)	4	27	48	49	20	24
Cu (d_{60}/ d_{10})	5.51	23.53	7.55	17.46	12.28	15.40
Cc($d_{30}^2/(d_{10} X d_{60})$)	1.93	1.13	1.27	0.48	1.86	3.06

According to Cheng et al. (2020), tailings are considered well graded when Cu ranges between 5 and 10 and exhibit higher compaction potential when Cc falls between 1 and 3. In this study, Cc and Cu were calculated to evaluate the gradation characteristics of each tailing sample. While these parameters provide quantitative insight into PSD, it is also essential to define the theoretical classification criteria to ensure consistency with geotechnical standards.

According to the Unified Soil Classification System (USCS) as defined in ASTM D2487 and the particle-size analysis procedure in ASTM D422, materials with Cc = 1–3 and Cu > 4 (for sands) or Cu > 6 (for gravels) are classified as well graded. This grading indicates a continuous PSD that minimizes voids and enhances particle interlocking, resulting in higher packing density and more stable rheological behavior. Accordingly, tailings with Cc = 1–3 were considered well graded in this study, consistent with ASTM and USCS definitions. Such gradation is known to promote better flowability and pumpability of paste formulations due to reduced interparticle friction and efficient packing of fine and coarse fractions.

Based on the results in Table 2, the iron, boron, silica, and marble tailings exhibit higher compaction potential (Cc > 1), whereas gold and copper tailings show lower values (Cc < 1). In terms of Cu, the iron and silica tailings are well graded. When considering the fine fraction (<20 µm), iron tailings have the lowest fine content (≈ 4%), whereas silica and gold tailings contain the highest amounts (≈ 48% and 49%, respectively). These variations in gradation and fine content are expected to significantly influence the rheological response of the paste mixtures.

2. Methods

Tailings homogenization and paste mixing were carried out as follows. As received tailings were air-dried. When initial moisture exceeded approximately 1%, samples were oven dried at 105±5°C to constant mass and then gently disaggregated by hand with a rubber mallet to avoid particle breakage. Each material was homogenized by cone and quartering and riffle-splitting until a representative composite was obtained, from which test aliquots were taken.

For each target volumetric fraction (VF), deionized water was dosed gravimetrically (±0.1%) to achieve the prescribed VF, as defined in Equation 1. Mixing was performed in a bench mixer using the following sequence: 1 min low-speed wetting, 3 min at 500 rpm, a 1 min rest for scraping, and 10 min at 500 rpm (total mixing time ≈ 15 min). The bowl was covered during mixing to minimize evaporation. Mixtures were conditioned for 60 s before testing to release entrained air.

All rheological tests were performed at 23°C using a vane spindle (diameter: 20 mm, length: 40 mm) in a 60 mm cup. The shear rate was increased from 0 to 200 s^{-1}, and shear stress was calculated from the measured torque according to Equations 2–3. The same procedure was applied to all tailings, and tests were performed in randomized order to minimize time-dependent effects.

Since the maximum packing density values were also determined in this study, volumetric solids ratios were used in the calculations. The solid content of each sample was expressed by the volume fraction (VF) defined in Equation 1. The corresponding weight fraction (WF) and volumetric fraction (VF) values of the paste mixtures are listed in Table 3.

$$\mathrm{VF} = \frac{Vt}{(Vt + Vw)} \tag{1}$$

VF – volumetric fraction,
V_t – volume of tailings,
V_w – volume of water.

Table 3. Weight fraction (WF) and volumetric fraction (VF) values of paste mixtures

Tabela 3. Wartości frakcji wagowej (WF) i frakcji objętościowej (VF) mieszanek pastowych

Samples	FeT (%)		BT (%)		SiT (%)		AuT (%)		MT (%)		CuT (%)	
	WF	VF	WF	VF	WF	VF	WF	VF	WF	VF	WF	VF
1	74	49.3	60	36.2	56	31.5	42	20.9	70	45.9	40	16.5
2	75	50.6	61	37.2	57	32.4	43	21.6	73	49.6	45	19.5
3	76	51.9	62	38.2	58	33.3	44	22.3	75	52.2	50	22.8
4	77	53.3	63	39.2	60	35.1	46	23.7	76	53.5	55	26.6
5	78	54.8	65	41.3	62	37.1	47	24.5			60	30.7
6			68	44.5	65	40.1	49	26.0			62	32.6
7			70	46.9	68	43.4					65	35.5
8			71	48.1	70	45.7					70	40.8

To determine the minimum and maximum WF and VF ratios at which the materials exhibit Bingham plastic behavior, rheometer measurements were conducted for each sample, starting from 5% WF and increasing by 5% increments. The values showing Bingham flow behavior are presented in Table 3. The rheological tests were carried out on all mixtures listed in the table, and the ranges where the materials behaved as paste-like were identified accordingly.

The vane method, which is especially suitable for dense suspensions, was used for all measurements. Other methods, such as cup and bob, are limited to a maximum solid content of about 72–73% when testing paste materials, which restricts their use despite providing good correlation with flow-loop data (Ahmed et al. 2022). The diameter and length of the vane spindle were 20 mm and 40 mm, respectively, and the container diameter was 60 mm, ensuring a gap at least twice the vane diameter. The torque measured at increasing shear rates (0–200 s^{-1}) was converted to shear stress using Equation 2 (Nguyen and Boger 1983):

$$\tau = T \cdot \frac{2}{\pi D^3} \cdot \left(\frac{H}{D} + \frac{1}{3} \right)^{-1} \tag{2}$$

↳ τ – shear stress (Pa),
T – torque (N·m),
D – vane diameter (m),
H – vane length (m).

Paste mixtures exhibit Bingham plastic flow behavior. The rheological model for Bingham-type fluids is given in Equation 3 (Kwak et al. 2005; Ihle and Tamburrino 2018):

$$\tau = \tau_0 \left(\frac{du}{dy} \right) \tag{3}$$

↳ τ_0 – yield stress (Pa),
η – plastic viscosity (Pa·s),
du/dy – shear rate (s^{-1}).

During rheology experiments, yield stress and viscosity values were obtained using Equation 3. In addition, the maximum packing density (ϕ_m) of each tailing was determined, representing the highest achievable solid content before mixing or pumping becomes impractical (Deng et al. 2018). To calculate this, viscosity values for different solid ratios at the same yield stress were determined and applied in Equation 4. Using graphical analysis, the points where the solid ratio equaled the packing density were identified, and the highest of these was taken as ϕ_m (Treger et al. 2010).

The clay content of all tailings was also measured using the methylene blue test, in accordance with EN 933-9.

$$\frac{\phi}{\phi_m} = \left(1 - \sqrt{\frac{\mu_0}{\mu}} \right) \tag{4}$$

↳ ϕ – solid content,
ϕ_m – packing density,
μ – viscosity of the suspension,
μ_0 – viscosity of water.

3. Results and discussion

Rheological tests were conducted on paste mixtures prepared with six different types of tailings (iron, boron, silica, gold, marble, and copper) at various volumetric fractions (VF). The relationship between shear stress and shear rate for these mixtures is presented in Figure 2.

The flow curves and yield stress results in Figure 2 indicate that the rheological behavior of the paste mixtures is strongly influenced by the particle size distribution (PSD) and

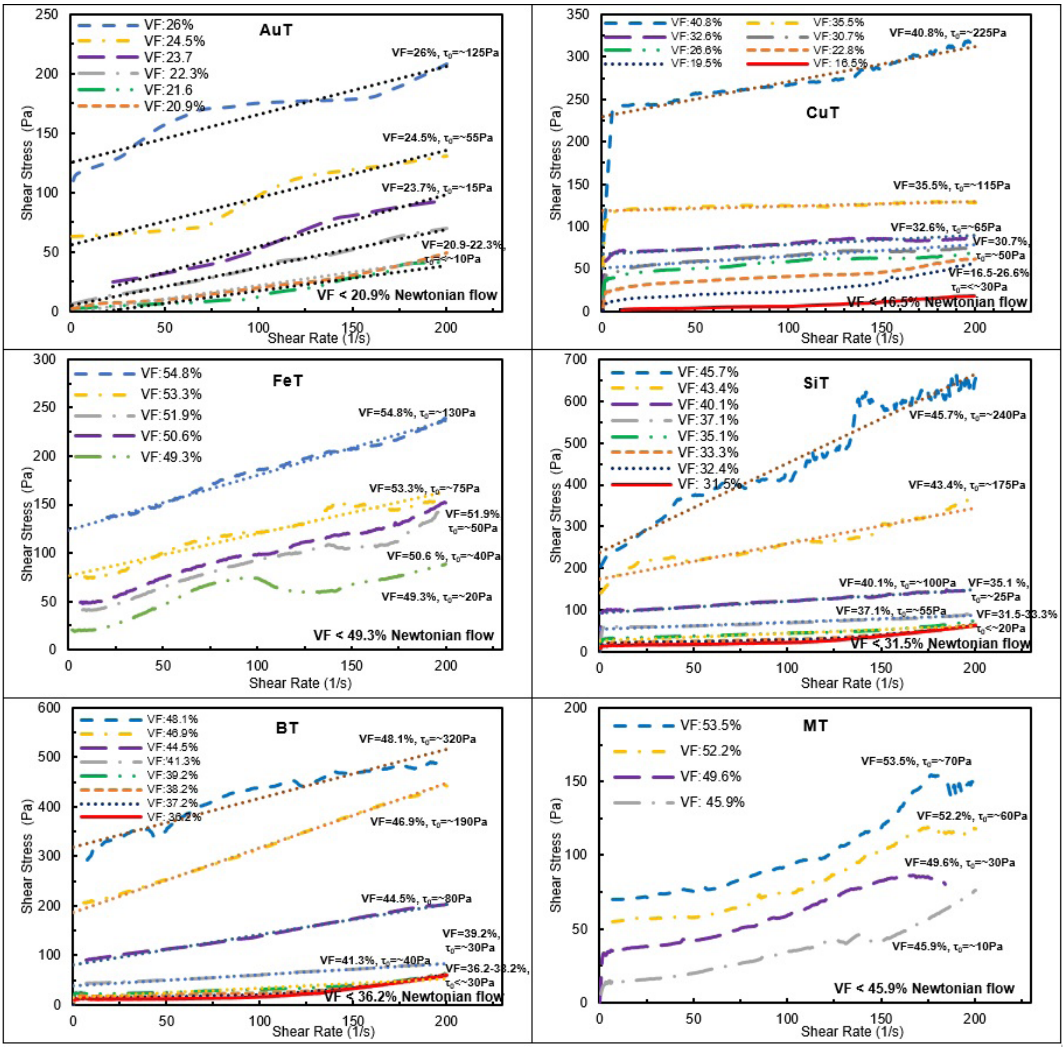

Fig. 2. Shear stress versus shear rate of the paste material containing AuT, CuT, FeT, SiT, BT and MT

Rys. 2. Naprężenie ścinające a szybkość ścinania materiału pastowego zawierającego AuT, CuT, FeT, SiT, BT i MT curvature coefficient (Cc) of the tailings. In general, samples with higher Cc values exhibited lower apparent viscosity and improved flowability, suggesting that a more uniform grain size distribution promotes efficient particle packing and reduces interparticle friction. However, physical factors alone cannot fully explain the observed variations in rheological performance among the tailing types.

The chemical composition of the tailings also had a significant influence on rheology. Specifically, the SO_3 content and clay fraction played dominant roles in determining the yield stress and apparent viscosity. Higher SO_3 levels favor the transient formation of ettringite, enhancing particle flocculation and cohesion, which in turn increases yield stress. Conversely, excessive sulfate may stiffen the microstructure, reducing flowability. Likewise, the presence of clay minerals (e.g., montmorillonite, muscovite) raises surface area and water adsorption capacity, thereby increasing viscosity while imparting thixotropic recovery during shear. These findings are consistent with recent studies reporting strong chemical rheological coupling in binder–tailings systems (Tuylu 2022b; Girskas et al. 2023; Koltsakidis et al. 2023; Menasria et al. 2025). Overall, both sulfate and clay contents contribute to the structural build-up and shear-thinning characteristics of tailings-based pastes.

Interestingly, the gold tailings (AuT) and silica tailings (SiT) exhibited apparently similar rheological behavior, despite their distinctly different particle size distributions. This can be explained by the combined effects of mineralogy and surface characteristics. The AuT samples, characterized by low curvature coefficients (Cc < 1), contain trace clay and sulfide minerals that enhance interparticle bonding and frictional resistance, increasing yield stress. In contrast, SiT samples, with a high fine fraction, consist mainly of fine silica particles that, while chemically inert, have high specific surface areas that increase water retention and surface friction. These two mechanisms, surface reactivity in AuT and high surface area in SiT, result in comparable apparent viscosities and yield stress values. Similar compensatory effects of surface activity and PSD were also reported by Menasria et al. (2025) and Koltsakidis et al. (2023).

The VF ranges used in the experiments were determined based on the intrinsic properties of the tailings, as flow behavior varied with material characteristics. As the solid content increased, the yield stress also increased (Zhang et al. 2021). In pastes with higher water content, particle–particle contacts decrease and the lubrication film thickens, facilitating easier particle movement during shear (Zhao et al. 2020). The VF range is therefore critical for paste design, as it defines the transition between Newtonian and Bingham-type behavior.

As shown in Figure 2, when VF values exceed 20.9%, 16.5%, 49.3%, 31.5%, 36.2%, and 45.9% for AuT, CuT, FeT, SiT, BT, and MT, respectively, the rheological behavior changes significantly. Below these limits, yield stress approaches zero, indicating Newtonian flow, whereas above these thresholds, mixtures exhibit Bingham-type behavior (Lang et al. 2015). Thus, the lower VF limits (Min VF) for paste formation were determined as 20.9% (AuT), 16.5% (CuT), 49.3% (FeT), 31.5% (SiT), 36.2% (BT), and 45.9% (MT). As expected, both yield stress and viscosity increased with solid content beyond these values. When VF exceeded 26%, 40.8%, 54.8%, 45.7%, 48.1%, and 53.5% for the same tailings, the pastes lost flowability and could no longer be measured rheologically due to excessive viscosity and yield stress.

As illustrated in Figure 3, yield stress begins to increase sharply beyond a critical VF value for each mixture. The Critical VF values were determined as 24.5% (AuT), 32.6% (CuT), 53.3% (FeT), 40.1% (SiT), 44.5% (BT), and 49.6% (MT). Exceeding these limits would substantially increase pumping costs; therefore, defining the critical VF is essential for paste design.

In comparison, Yowa et al. (2022) reported that increasing solid content from 74% to 78% in cemented paste fill raised yield stress from ~100 Pa to ~400 Pa, confirming that rheology is highly sensitive to solid concentration. The packing density and methylene blue values for the present tailings are given in Table 4.

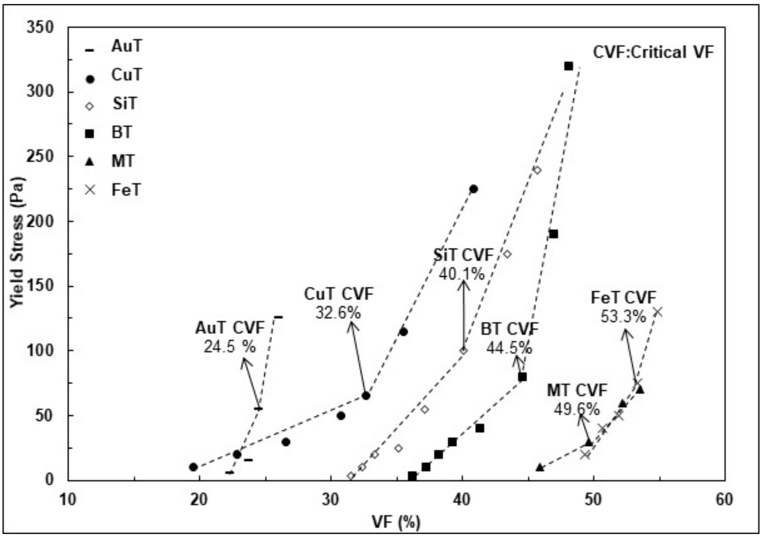

Fig. 3. Variation of yield stress with volumetric fraction (VF)

Rys. 3. Zmienność granicy plastyczności w zależności od frakcji objętościowej (VF)

Table 4. Packing density and methylene blue values of paste materials with different tailings

Tabela 4. Gęstość upakowania i wartości błękitu metylenowego materiałów pastowatych z różnymi odpadami

Tailings	FeT	BT	SiT	AuT	MT	CuT
Packing density (%)	55.2	48.5	46.20	26.1	54.90	41.50
Methylene blue value (g/kg)	12.0	25.0	2.75	19.5	1.25	1.75

The highest packing density was observed in FeT (55.2%), while AuT had the lowest (26.1%). Boron tailings (BT) had the highest clay content, with a methylene blue value of 25 g/kg, whereas marble tailings (MT) showed the lowest value (1.25 g/kg). Notably, there was no direct correlation between clay content and packing density. In paste design, the Min VF, Critical VF, and packing density are important parameters influencing cost and pumpability, and these vary considerably depending on tailing characteristics.

Although previous studies emphasized the proportion of fine particles, the present results indicate that the fine fraction alone is not a sufficient predictor of rheology. Landriault (2001) suggested that tailings should contain at least 15% particles smaller than 20 μm to achieve paste consistency. However, FeT with only 4% <20 μm exhibited the highest Min VF, Critical VF, and packing density, suggesting that PSD shape (gradation) is a stronger determinant than fine content alone.

The relationships between Cc and the rheological parameters are illustrated in Figures 4–6.

As shown in Figures 4 and 5, tailings with Cc between 1 and 3 (FeT, SiT, BT, MT) exhibited Min VF values above 30% and Critical VF values above 40%. In contrast, tailings with poor gradation (AuT, CuT) had Min VF around 20% and Critical VF near 30%. Similarly, Figure 6 shows that well graded materials (1 < Cc < 3) achieved higher packing densities (>45%), whereas poorly graded AuT (Cc < 1) had ~25%. The CuT paste (Cc > 3) reached ~40%, likely due to its low clay content.

A high Min VF, Critical VF, and packing density are advantageous for tailings disposal, as more solids can be placed per unit of pumping energy. Well-graded tailings thus enable efficient paste formation without excessive viscosity. In ideal conditions, packing

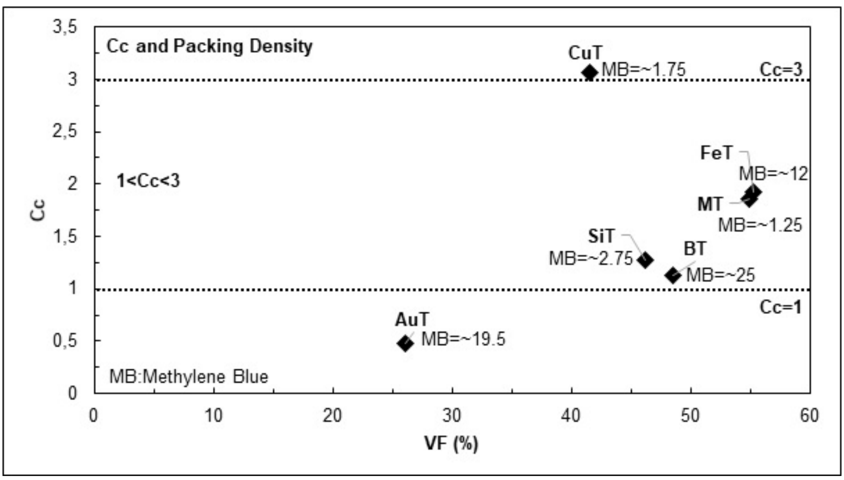

Fig. 4. Relationship between minimum VF and curvature coefficient (Cc)

Rys. 4. Zależność między minimalną wartością VF a współczynnikiem krzywizny (Cc)

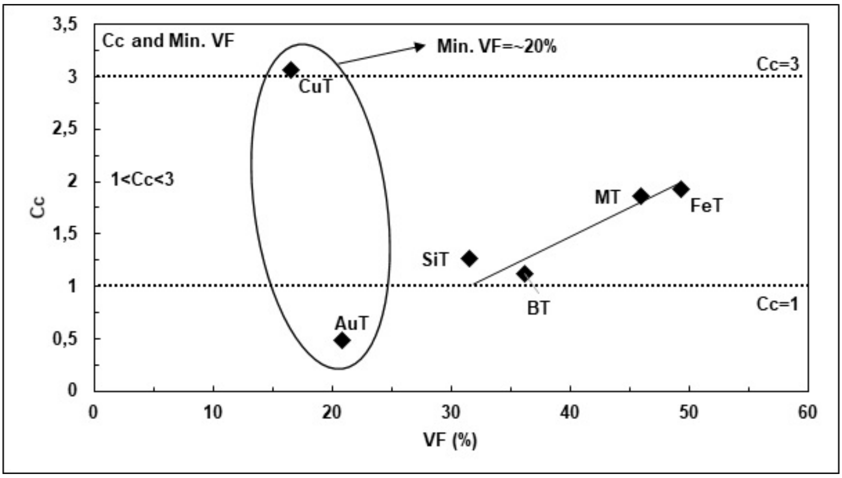

Fig. 5. Relationship between critical VF and curvature coefficient (Cc)

Rys. 5. Zależność między krytyczną częstotliwością VF a współczynnikiem krzywizny (Cc)

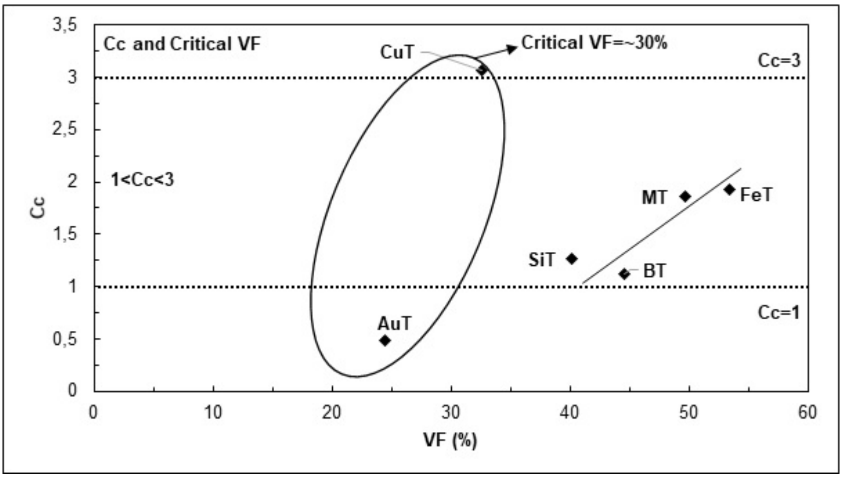

Fig. 6. Relationship between packing density and curvature coefficient (Cc)

Rys. 6. Zależność między gęstością upakowania a współczynnikiem krzywizny (Cc)

density depends on gradation rather than particle size. Cheng et al. (2020) demonstrated that combining cement (packing density 0.47) with unclassified nickel tailings (0.54) in optimized ratios yielded the highest paste packing density. Similarly, increasing packing density leads to higher yield stress (Deng et al. 2018) due to the reduced lubricant film thickness and increased particle contact. Poor gradation produces a similar frictional effect, hindering relative particle movement.

Hence, the packing density, Min VF, and Critical VF all increase with improved gradation. Yue et al. (2016) showed that, in coal tailings pastes, yield stress first decreases and then increases as coarse particle content rises, with optimal flow occurring at 10–15% coarse fraction. This confirms that particle gradation directly affects rheology. Similarly, Zhang et al. (2023) and Mahboub et al. (2022) reported strong correlations between slump value, Cu, and Cc ($r > 0.80$) in Pb–Zn tailings, highlighting that a balanced PSD promotes both stability and flowability. In paste mixtures containing excessive coarse particles, fine particles cannot fill voids effectively, reducing suspension stability. Conversely, an overabundance of fine particles increases viscosity. Well-graded tailings avoid both extremes, maintaining homogeneous, non-settling, and pumpable pastes (Shrestha 2014).

Overall, these results confirm that the particle size distribution and curvature coefficient (Cc) are key parameters controlling the rheological behavior, packing density, and pumpability of tailings-based paste materials.

Conclusion

Pumping costs and paste design parameters vary depending on the physical and mineralogical properties of the tailings. Among these, the particle size distribution (PSD) plays a decisive role in determining the rheological behavior and pumpability of paste materials. Therefore, accurate characterization of PSD is essential when designing paste mixtures.

In this study, pumpability conditions were evaluated for the disposal and storage of gold (AuT), copper (CuT), iron (FeT), boron (BT), marble (MT), and silica (SiT) mine tailings as paste materials, and the following conclusions were drawn:

- *Minimum volumetric fraction* (Min VF): The lower VF limits required for paste formation were determined as 20.9%, 16.5%, 49.3%, 31.5%, 36.2%, and 45.9% for AuT, CuT, FeT, SiT, BT, and MT, respectively. Below these limits, paste consistency does not form, and the mixtures behave as Newtonian fluids.
- *Critical volumetric fraction* (Critical VF): When VF exceeds a certain critical value, yield stress increases sharply, and pumpability decreases. The Critical VF values were determined as 24.5%, 32.6%, 53.3%, 40.1%, 44.5%, and 49.6% for AuT, CuT, FeT, SiT, BT, and MT, respectively. Beyond these limits, pumping costs are expected to rise significantly due to the higher viscosity and yield stress.
- *Packing density and clay content:* The maximum packing density and methylene blue values of the pastes were also determined. The highest packing density (55.2%) was obtained for FeT, whereas AuT had the lowest (26.1%). The boron tailings (BT) exhibited the highest clay content (25 g/kg), while marble tailings (MT) had the lowest (1.25 g/kg).
- *Effect of fine fraction content:* The presence of fine material alone was found to be insufficient to explain the rheological behavior of the paste. FeT, which contained

only 4% particles smaller than 20 µm, achieved the highest Min VF, Critical VF, and packing density values among all tailings, emphasizing that overall gradation exerts a stronger influence than fine fraction content alone.

- *Effect of curvature coefficient* (Cc): The curvature coefficient, which reflects the particle size distribution of tailings, showed a strong correlation with rheological performance. Well-graded tailings (1 < Cc < 3; e.g., SiT, BT, MT, FeT) exhibited Min VF values above 30% and Critical VF values above 40%, whereas poorly gradedmaterials (Cc < 1 or > 3; e.g., AuT, CuT) had lower Min VF (~20%) and Critical VF (~30%) values. Such low values are disadvantageous for paste disposal because less solid material can be transported at the same cost, while well-graded tailings reduce pumping costs and enhance operational efficiency.

Overall, the results demonstrate that changes in the particle size distribution and curvature coefficient (Cc) of tailings have a significant impact on the rheological behavior, packing density, and pumping performance of paste materials. Hence, controlling and optimizing particle gradation in tailings is critical for designing sustainable and cost-effective paste disposal systems.

Abbreviations

AuT – Gold mine tailings
BT – Boron mine tailings
CuT – Copper mine tailings
FeT – Iron mine tailings
SiT – Silica mine tailings
MT – Marble mine tailings
Cc – Curvature coefficient
Cu – Uniformity coefficient
WF – Weight fraction
VF – Volumetric fraction
Min VF – Minimum volumetric fraction
V_t – Volume of tailings
V_w – Volume of water
τ – Shear Stress
T – Torque
D – Vane diameter
H – Vane length
τ_0 – Yield stress (Pa)
du/dy – Shear rate (s^{-1})
η – Plastic viscosity (Pa s)
ϕ – Solid content

ϕ_m – Packing density
μ – Viscosity
μ_0 – Viscosity of water

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THE EFFECT OF PARTICLE SIZE DISTRIBUTION OF TAILINGS ON RHEOLOGICAL CHARACTERIZATION OF PASTE

Keywords

tailings paste, rheological properties, pumping behavior, packing density, particle size distribution

Abstract

The rheological behavior of paste, particularly regarding pumpability and in-situ dispersion, is critical for the safe and efficient disposal of mine tailings using paste technology. Therefore, when designing paste mixtures, both rheological and physical mechanical properties must be well defined. The flow behavior of paste is mainly governed by the physical and chemical characteristics of the tailings, among which the particle size distribution (PSD) plays a decisive role. In this study, process tailings from six different mines, iron, boron, silica, gold, marble, and copper were characterized, and the rheological behavior of pastes prepared with each tailings type was examined. The results revealed a clear relationship between the curvature coefficient (Cc), which reflects PSD, and the rheological parameters of the paste. Mixtures containing tailings with Cc values between 1 and 3 (classified as well-graded) exhibited superior rheological performance and pumpability despite having higher solid contents. In contrast, tailings with Cc < 1 or Cc > 3 showed reduced flowability and higher viscosity.

For example, the packing density of gold tailings with Cc < 1 was approximately 25%, whereas that of iron tailings with Cc ≈ 1.9 reached nearly 55%. These findings confirm that variations in PSD, as represented by the curvature coefficient, have a significant impact on the pumpability and flow behavior of paste mixtures, offering practical insights for sustainable tailings disposal design.

WPŁYW ROZKŁADU WIELKOŚCI CZĄSTEK ODPADÓW KOPALNIANYCH NA WŁAŚCIWOŚCI REOLOGICZNE PASTY

Słowa kluczowe

pasta odpadowa, właściwości reologiczne, właściwości pompowania,
gęstość upakowania, rozkład wielkości cząstek

Streszczenie

Właściwości reologiczne pasty, zwłaszcza jej pompowalność i dyspersja in situ, mają kluczowe znaczenie dla bezpiecznego i wydajnego usuwania odpadów kopalnianych przy użyciu technologii pastowej. Dlatego podczas projektowania mieszanek pastowych należy dokładnie określić zarówno właściwości reologiczne, jak i fizyczno-mechaniczne. Zachowanie pasty podczas przepływu zależy głównie od właściwości fizycznych i chemicznych odpadów, wśród których decydującą rolę odgrywa rozkład wielkości cząstek (PSD). W niniejszym badaniu scharakteryzowano odpady procesowe z sześciu różnych kopalń żelaza, boru, krzemionki, złota, marmuru i miedzi oraz zbadano właściwości reologiczne past przygotowanych z każdego rodzaju odpadów. Wyniki wykazały wyraźny związek między współczynnikiem krzywizny (Cc), który odzwierciedla PSD, a parametrami reologicznymi pasty. Mieszanki zawierające odpady o wartościach Cc pomiędzy 1 a 3 (sklasyfikowane jako dobrze uziarnione) wykazywały lepsze właściwości reologiczne i pompowalność pomimo wyższej zawartości substancji stałych. Natomiast odpady o Cc < 1 lub Cc > 3 wykazywały zmniejszoną płynność i wyższą lepkość. Na przykład gęstość upakowania odpadów złota o Cc < 1 wynosiła około 25%, podczas gdy gęstość upakowania odpadów żelaza o Cc ≈ 1,9 osiągnęła prawie 55%. Wyniki te potwierdzają, że zmiany PSD, reprezentowane przez współczynnik krzywizny, mają znaczący wpływ na pompowalność i właściwości przepływowe mieszanek pastowych, dostarczając praktycznych informacji przydatnych przy projektowaniu zrównoważonych systemów utylizacji odpadów.